On the Studies of Space: in Physics and Metaphysics

by

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Contents

Outline

In this essay, I will discuss and analyse the nature of space from both historical and modern perspectives, as well as from physics and metaphysics perspectives. The argument about the nature of space is usually regarded as the debate between two doctrines, substantivalism and relationalism. Substantivalism is a doctrine positing space, as an independent existence. Whereas, relationalism is a doctrine regarding space as relational and to say that space as an independent existence is redundant and superfluous, as relationalists argue that one can still get to various prominent theories without referring to substantial space. Hence, relationalism is a preferable background in doing physics. To resolve the problem between substantivalists and relationalists, one needs to look at what substantial space, or space as an independent existence, really means. Then, I argue that, either from historical or modern physics, some theories, if not many, still have a sort of substantial space lurking under these theories, even though it is not explicitly implied. Additionally, I argue that, from a metaphysical standpoint, it is impossible to conceive without space. In other words, space is a necessary condition for conceivability. So, if we can conceive, there must be a space.

This essay is divided into five chapters and some sections. In the first chapter, the historical expositions of the nature of space will be articulated. Two leading figures, Issacs Newton and Gottfried Wilhelm Leibniz, will be discussed to help with the articulation of the nature of space. In the second chapter, the modern picture of the argument between substantivalists and relationalists will be introduced. Additionally, I will briefly talk about some geometry. To help the overall argument, some studies of geometry is necessary. In chapter three, with all the geometry knowledge in chapter two, we will be able to see how relationalists can reformulate a substantivalists' theory, Newton's mechanics, into a relationalists' theory. In chapter four, I will be focusing on the essence of the argument between substantivalism and relationalism. That is I will be looking at what exactly they are at odds. Once we have a clearer picture regarding their disagreement, I will argue for substantivalism in chapter five. In chapter five, I will conclude that the notion of space is indispensable.

Chapter 1: Historical debate on the Nature of Space

1.1 Introduction

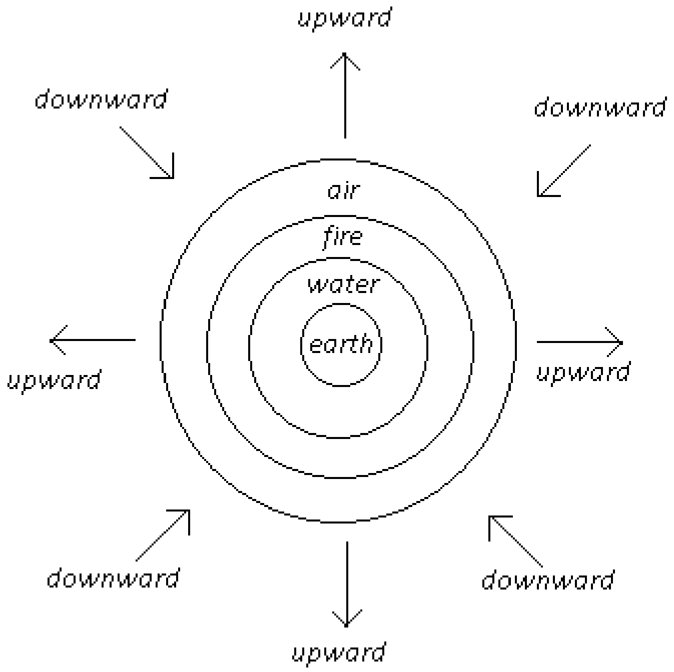

Figure-1.

Aristotle can be seen as the first who systematically formulates the theory of motion. Aristotle believes that every object has their own 'natural motions'. The reason for these motions happen is because every element has their own natural place and they want to go back to their natural place. For example, the natural motion of the earth elements, such as stones and rocks, is to move 'downward', as their natural place is at the centre. So, it explains why stones fall on the ground. The water element has 'downward' natural motion too, but with less initiative than earth, as a stone will sink down in water. The fire elements and the air elements have the tendency to move 'upwards'. When something moves downwards, Aristotle means that it moves to the centre. Similarly, when something moves upwards, it moves away from the centre (Maudlin, 2012, p. 2). Since all the earth elements move down to the centre, it then forms the planet earth. All the air elements move upwards, away the centre. Hence, it forms the sky. Considering Aristotle's theory of motion, it gives a rough idea to the world Aristotle believes in (see figure-1). Aristotle's theory of motion provides a picture of the nature of the space, although Aristotle himself may not have this intension. The notion 'centre of the universe' makes sense in Aristotelian space, which is the natural place for the earth elements. The notions, 'upwards' and 'downwards', are too well-defined for Aristotle. Centuries after Aristotle, Issacs Newton develops a new theory to replace Aristotle.

1.2 Newton's Space

In the early development of the theory of motion, Newton's mechanics is the leading theory. In the first chapter of Newton's *Principia*, 'Scholium', Newton involves two crucial, but controversial, definitions or postulates in his theory of motion, viz. absolute space and absolute time.

- *'Absolute, true, and mathematical time, of itself, and from its own nature, flows equably without relation to anything external, and thus without reference to any change or way of measuring of time…'* (Newton, 1729, p. 6)
- *'Absolute space, in its own nature, without relation to anything external, remains always similar and immovable. Relative space is some movable dimension or measure of the absolute space…'* (Newton, 1729, p. 6)

In this context, absoluteness has the sense of independent existence. It does not depend on relations between matters, objects or entities. That is if all matter in the universe were to be removed, what remains, for Newton, is the absolute space and absolute time.

Introducing absolute space and absolute time into his theory of motion allowed Newton to derive several significant notions and then his first law of motion. The concept of absolute time allows him to define absolute simultaneity and absolute duration between events (Earman, 1989). Following this idea, it is meaningful to ask questions like 'do event A and event B happen at the same time', 'how long does event B take after event A' and so on. On the other hand, absolute space has the features of immovability and similarity, which allows him to derive *absolute motion* and *absolute rest*. That is a body is at absolute rest, when it remains at the same position in absolute space through time. Whereas, a body is in absolute motion, when it translates from one point, in absolute space, to another point in absolute space (Earman, 1989).

Newton does not postulate absolute space and absolute time just for metaphysical purposes[1], but, most importantly, also for his first law:

> *Every body continues in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed upon it* (Newton, 1729, p. 13).

At the first glance of the first law, there may be some vagueness embedded in the terms 'rest' and 'uniform motion'. However, as soon as the concepts of absolute space and absolute time come into the picture, Newton is able to define it in term of absolute space. For example, 'something moves, or rests, absolutely' means that it moves, or rests, relative to absolute space (Huggett and Hoefer, 2015).

Moreover, Newton's first law is closely related to *Galilean Relativity*, which basically state that there is no observable difference between a rest state and a uniformly moving state. That is to say, a free body – a body with no acceleration or force impressed upon it – is either a rest state or a uniformly moving state relative to absolute space and it is impossible to feel or sense which states it is actually in. We will discuss this in more detail in a latter section.

1.2.1 The Geometry of Newtonian Absolute Space: Euclidean Space

Newtonian absolute space has the geometrical structure of three-dimensional Euclidean space E^3, which can be characterised by its *symmetries*. A symmetry can be seen as a test, to test what happens after, and before, a transformation or change is performed on an entity. If the entity remain the same structure as before, once the transformation has performed, this transformation is called a symmetry of the entity (Rickles, 2016, p. 29). In general, symmetry is a sort of 'change without change', as Rickles (2016, p. 29) puts it. In the case of E^3, it is characterised by being *homogeneous*, (which is a translational symmetry), and *isotropic*, (which is a rotational symmetry) (Maudlin, 2012, p. 34).

[1] Robert Disalle (2009) would disagree with this claim. Disalle believes that Newton introduces the notion of absolute space and absolute time only by the means of definitions, not metaphysical claims. In this way, Newton absolute space and absolute time can escape the criticism of Leibniz's shift and boost argument.

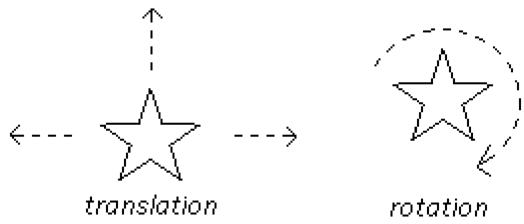

Figure-1.

For example, if all things in E^3 are moved (or 'translated') with some distances in certain direction or reoriented by rotation with some degree, clockwise or anti-clockwise, all geometrical relations among points or objects will remain the same.

1.2.2 Newton's Bucket Experiment

It is important to note that Newton himself realises that the true motion and the relative motion are indistinguishable via observations from human's senses, as absolute space itself is empirically unobservable (Newton, 1729, p. 8). For this reason, Newton claims, instead of the absolute ones, the relative notion should be used. By relative notion, he means that the states of motion are in relation to something observable, like a planet or a star. However, Newton does not simply regard relative motion as true and primitive. Instead, Newton attempts to show the existence of absolute motion and, hence, absolute space, via his bucket experiment. Consider a bucket filled with water, the bucket is rotated around its central axis. What will be observed is that the water in the bucket, which is initially flat, becomes concaved (Newton, 1729, p. 10). Notice that the water is initially at rest relative to the bucket's inner surface, when the bucket is in its final stage, the water is spinning together with the bucket at the same rate, meaning that the water is still at rest relative to the bucket. However, from the initial stage to the latter stage, the difference is that the water becomes concaved in the bucket (see figure-3). In Newtonian mechanics, rotation is a form of acceleration and acceleration is the rate of change of velocity. Now, the question is that what does the bucket accelerate relative to? For Newton, the rotational motion of the water must not relative to the bucket, since the water is at rest relative to the bucket. Rather, the only explanation for the concaved water is that it is rotated, or accelerating, relative to the absolute space. So, from the bucket's argument, one can conclude that acceleration is absolute as it accelerates relative to absolute space.

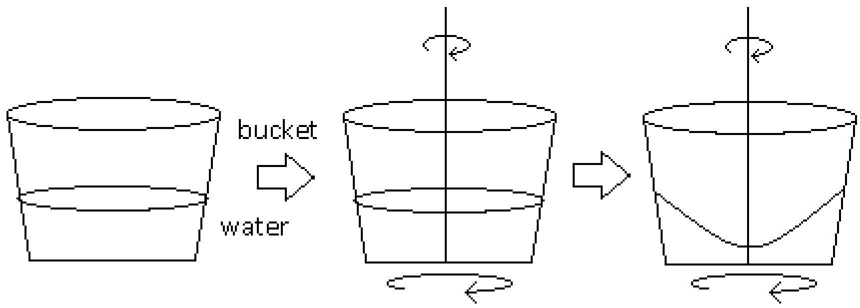

Figure-2.

1.3 Leibniz’s Space

On the other side of the battlefield, there is Newton’s opponent, Gottfried Wilhelm Leibniz. Leibniz argues against Newton that space is merely the order of coexisting things and not a substantial space. The same goes to the concept of time. Time is just the order of non-contemporaneous things (Reichenbach and Cohen, 1978, p. 52). Hence, space and time are only relations between objects and entities. For Leibniz, space is like a family tree, which is nothing but just relations between one another in a family, such as the notions ‘father’, ‘mother’, ‘brother’, ‘sister’, ‘aunt’, ‘uncle’ and so on (McDonough, 2014). Without all these relations, there will be no family trees. Analogically, the notion ‘father’ is not a thing that exists independently, but a relation between two people, and only people, in this context, are real. For this reason, Leibniz’s theory of motion appears to be different from Newton’s ones. For Leibniz, the state of motion of a particle is not relative to absolute space, but only relative to something observable. Saying that a particle is moving, it only makes sense when there exists another entity, which can be regarded as a reference, viz. the particle is moving relative to another entity.

1.3.1 Leibniz’s Thought Experiments

In response to Newton, Leibniz makes use of the characteristic of symmetry in Newtonian absolute space. He gives two different, but similar, kinds of thought experiments, static shift and kinematic shift experiments. Leibniz then provides two distinct arguments against Newton, the Principle of Sufficient Reason Argument (PSR Argument) and the Principle of Identity of Indiscernibility (PII Argument).

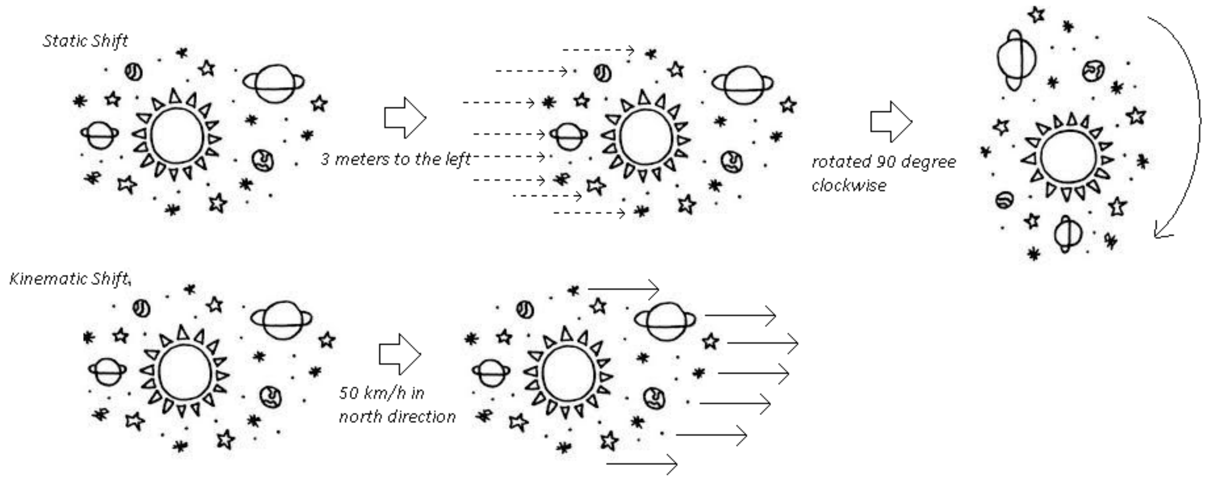

Figure-3.

Leibniz argues that the notion of absolute space implies an infinite number of possible ways which our universe could be, in either statically or kinematically (Dasgupta, 2015, p. 606). In static shift experiment, there are possibilities where the universe could be shifted slightly, say three meters to the left; rotated 90 degree in clockwise or flipped from left to right. In this sense, there are infinite number of such ways the universe can be shifted. If Newtonian absolute space is true, then each static shifted model of the universe is different from another. Furthermore, there are also infinitely many possibilities where the universe could be shifted kinematically. The universe can be boosted with certain velocity, like 50 km/h in the north direction or with half of the speed of light in south direction. Again, if Newtonian absolute space is true, then each kinematic shifted model of the universe is different from another.

However, none of these possibilities, if anyone of them were to be true, would make any physical changes, compared to our actual world. As mentioned above, Newtonian absolute space is a three-dimensional Euclidean space, E^3, and Euclidean space is both homogenous and isotropic. So, any translational or rotational transformations would not make any physical differences. Furthermore, according to Galilean Relativity, a rest state and a uniformly moving state are indiscernible. So, whether the universe is moving with certain speed or at rest, relative to the absolute space, there will be no empirical evidence. In other words, questions like ‘where exactly is our universe in absolute space?’ or ‘is the universe in uniform motion or absolute rest; if the universe is in uniform motion, what is the velocity?', can never be satisfactorily answered[2].

The kinematic and static shift experiment alone cannot do harm to Newtonian absolute space. However, two distinct principles Leibniz further introduces, together with the shift experiments, will work as arguments against Newtonian absolute space.

1.3.2 PSR Argument

In one argument of Leibniz, he appeals to the Principle of Sufficient Reason, or PSR:

> *Everything happens for a reason and it is impossible for something to happen without any reason.*

This tells us that if something happens in a particular way rather than another, there must be a reason why it is so. Leibniz claims that if space is a Newtonian absolute space, God, the creator of the universe, will have trouble creating the universe in such a space. Taking any part of Euclidean space, due to its characteristic of symmetry, one part of the space does not differ in any respect whatsoever from another part of space. There will be no reason why the content of our universe should be placed, or created by God, the way it is now rather than another (say, with everything three meters to the north) because it seems to be the case that every possibility is equally good (Maudlin, 2012, p. 37). There is no so-called better way to place or create the universe. Thus, this violates Leibniz's PSR principle.

1. If Newtonian absolute space is true, then there are infinitely many possible ways, in which the universe can be placed, and every possibility is equally good.
2. If there are infinite equally good possibilities to place the universe, there is no reason to place the universe one way instead of another.
3. If PSR is true, then there must be a reason why the universe is placed the way it is rather than another (God's reason)
4. PSR is true

[2] Maudlin (1993) actually answers the former question, namely our universe is *right here*. It is not over there, not 3 meters to the north, but *here*.

5. Newtonian absolute space is false

1.3.3 PII Argument

The second principle Leibniz appeals to is the Principle of Identity of Indiscernibility, or the PII:

> *For all A and B, if A and B have exactly the same properties then A and B are identical.*

That is if the properties of A and B are indiscernible, then A and B are just the same entity under different names. If the Principle of Identity of Indiscernibility is true, then the infinitely many possible models are just one and the same model under different names because according to Galilean relativity, it would be impossible to tell them apart. Hence, Newton must be committed to some metaphysical error (Maudlin, 2012, p. 41). To formalise Leibniz's PII argument,

1. If Newtonian absolute space is true, then there will be difference between the shifted and the un-shifted universe. (Symmetry)
2. If PII is true, then there is no difference between shifted universe and the un-shifted universe.
3. PII is true
4. Newtonian absolute space is false

1.4 Some Comments on PSR and PII

Leibniz's PSR and PII arguments, despite their validity, are flawed. In this section, I will argue that the PSR, as a principle itself, is implausible because it is self-undermining[3]. On the other hand, I will provide two arguments against PII. Assumes that PII is true, the way Leibniz argues against Newton does not take Newtonian absolute space seriously. Conversely, if Newtonian absolute space is taken seriously, then PII is not a principle, which can against absolute space. Another argument is from Max Black, who argues that PII, as a principle, itself fails to hold. Now, even if PII were to hold, PII is, too, in favours of substantivalism.

[3] In a later section, I will argue that even if the argument against PSR can be dismissed, PSR is actually in favours substantivalism instead of relationalism.

If PSR is true, then what is the reason for PSR to hold? If there is no reason for PSR to hold, then this would seem to be a violation of PSR, and so PSR is false. One solution for Leibniz may be that God is the reason for PSR. If that is true, then the next question is this: what is the reason for God being the reason for PSR to hold. One can always come out with the next 'why question' as long as there is an answer for the previous question. Along this line, it is either, at some point, one of the answers must be self-caused, or, the enquiries go on forever by following Socrates questioning method, 'what is the reason for *A*'; '*B* is the reason for *A*'; 'why *B*'; 'it is because *C*'; 'why *C*' and so on. The answer cannot be self-caused if PSR is true. If the enquiries go on forever, one can still ask a question why the enquiry goes on forever, if PSR is true. Hence, in this sense, the PSR is not plausible.

Leibniz's PII argument is also problematic, since it does not take the notion of Newtonian absolute space seriously. To argue for Newton in this context, the proposition 1 above, I suggest, should be that:

1*. If Newtonian absolute space is true, then there will be ontological differences between the shifted and the un-shifted universe.

By ontological differences, I mean that there are genuine differences between shifted and un-shifted universes, whether or not these differences are observable. As Maudlin (Maudlin, 1993, p. 189) rightly points out, the shifted universes are observationally indistinguishable, but they are ontologically distinct. That is if absolute space is true, then there will be a genuine difference between shifted and un-shifted universe. Nevertheless, the differences are empirically and observationally indistinguishable. In this interpretation of Newtonian absolute space, it is safe to assume that Newton is making metaphysical or ontological claim about space. In this sense, Newton can reply to relationalists that although absolute space is empirically unobservable, as Newton himself also realises, ontologically there exists an absolute space. In this context, PII should be reformulated as PII*:

For all A and B, if A and B have exactly the same ontological properties, then A and B are identical.

Another way to see why PII* should be the right interpretation is to consider a case. Imagine that there is a ball, say ball *A*, on a table, you pick up the ball and carefully observes the properties of the ball, like colour, texture, shape, weight and so on, say you have observed every *physically observable* property of the ball. You put the ball back to the table and walks away. A few minutes after, you come back to the same place and see a ball, say ball *B*, on the table. You pick it up and carefully observes the properties of the ball, like how you did just now. Then, you realise that ball *B* has exactly the same properties as ball *A*. Now, the question is that is it safe to conclude that ball *B* is the same as ball *A*, but just under different names. Now if you consider PII, which is used to argue against Newton, you would need to answer 'yes, they are the same ball', because you cannot observe any different properties between ball *A* and ball *B*. However, consider this: it may be the case that, during the few minutes, someone change ball *A* into another identical ball, which we name it ball *B*. In this case, ball *A* and ball *B* are clearly not the same despite their physical and empirical sameness because ball *A* and ball *B* are ontologically distinct. The same mistake happens in Newton case. If Newton absolute space is true, then there are differences between the shifted and the un-shifted universe in absolute space, despite that the differences are unobservable. So, Leibniz cannot conclude that, by the PII*, the shifted and un-shifted universes are the same, simply because the difference is not observable. In this sense, I would say PII* is more careful and stricter than PII. Unlike PII*, PII only consider physical and empirical observables.

Additionally, not even PII fails to become an argument against Newtonian absolute space. It even becomes an argument for Newtonian absolute space. This result is due to Max Black. Black (1952) invites us to imagine two spheres in an otherwise empty space. These two spheres, say, are made of iron; both have one meter in diameter; they have same colour, temperature etc; two spheres are one light-year apart (Black, 1952). Now, a problem comes into the picture, when questions, like 'how can we distinguish one sphere from another?', are asked. For Black, the motif of this thought experiment is to show the failure of PII, as PII fails to distinguish these two exactly identical spheres. Nevertheless, there is another way to solve this problem without PII being fail. Intuitively, since the two sphere are identical, the way to distinguish them is their properties in space. For instance, the first sphere is at a location one light year away to the, say, north from second sphere and the second sphere is located at one light year away to the south from the first sphere. Despite their all their identical properties, their spatial properties are different. Hence, PII holds. Yet, there is a price for Leibniz to pay for this solution, namely Newtonian absolute space must hold. To distinguish the two spheres from their spatial properties, like direction and distance, it only works in Newtonian absolute space. That means that, for Black, like Leibniz, their spatial properties are relational. Saying that first sphere is located at one light year away to the north from second sphere is no more than saying that second sphere is located at one light year away to the north from first sphere. In this sense, spatial properties cannot be the properties to distinguish two sphere, as their spatial properties are identical too. Hence,

If PII holds, Newtonian absolute space holds

If Leibniz wants Newtonian absolute space to fail, he has to give up PII as well.

Chapter 2: Modern debate on the Nature of Space

In this chapter, I will focus on the modern debate between substantivalism and relationalism. Moving from classical to modern, some contents of debate has slightly changed. The debate becomes more sophisticated and technical due to the improvement of physics. To help the articulations in my argument, I will bring out some studies of geometry.

2.1 Tension between Relationalism and Substantivalim

In putting the debate between Newton and Leibniz into philosophy of modern physics viewpoint, their argument can be seen as the argument between substantivalists and relationalists, where Newton and Leibniz, respectively, are the pioneers.

Relationalists, like Leibniz, think that space is not self-subsistent. Space is relational or dependent: the concept of space depends on other objects. The view of relationalists about space can be understood from asking the question, 'how can space be recognised?' Within the bound of intuition, the way we acknowledge physical space has certain evident characteristics, such as *distances, positions, directions* and so on. Therefore, it may be safe to assume that, intuitively, we acquire the notion of space through nothing but these characteristics. However, distances, positions and directions *per se* cannot be empirically observed. They are observed by means of observable physical objects, things, or in a spacetime context, *events*. The concept of distance is understood or defined as the space between two objects. The position and direction of an object, A, can only be meaningfully asserted when there exists another object, B, as a reference point, to talk about where A is located and which direction from B.

If space is understood in virtue of these characteristics, like *distances*, *positions* and *directions*, then it may be ideal to see space in term of these features. So, relationalists generalise the concept of space as below:

1. Empirically, the notion of space is acquired through *distances*, *positions* and *directions*.
2. *Distances*, *positions* and *directions* can only be understood in term of relations.

C. Therefore, space can only be defined in term of relations.

Thus, it is not surprising how relationalists formulate the concept of motion. Motion is the change of position, relative to another body. If two free-bodies, A and B, are moving away from each other, we know this because there exists an observable fact that is the distance between A and B becomes greater as time passes, with the rate of v_1 m/s (see figure-4). Empirically, this is the only physical observation. If that is true, then below three cases are essentially equivalent for relationalists. The only difference is that they are assigned by different inertial frames of reference.

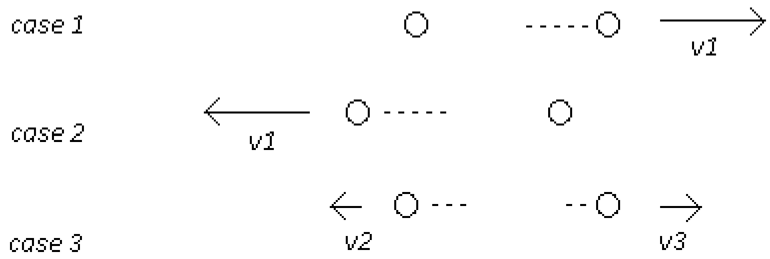

Figure-4.

Where $v_2 + v_3 = v_1$

Hence, the central concepts of *Spacetime Relationalism* can be formulated as:

1. Spacetime is a set of relations among objects or events.
2. Spacetime has no independent existence.

On the other hand, substantivalists, like Newton, think that space is something more than just a set of relations among objects. Space has its own independent existence. For Newton, space is substance-like. It is not a substance in the sense that ordinary physical objects are. It is a substance in the sense that space is self-subsistent. There are many forms of substantivalism, like manifold substantivalism, metric field substantivalism and so on. Regardless the differences between substantivalisms, all substantivalists share the views:

1. Spacetime has its own independent existence.
2. Spacetime is not a set of relations among objects or events.

If the above are really the core concepts of relationalism and substantivalism, then they are incompatible. As one can see, the first claim and the second claim of substantivalism and relationalism is about *what space is* and *what space is not*. For substantivalists, 'what space is' is 'what space is not' for relationalists and vice versa.

2.2 Spacetime Representation

To understand Newton's ideas of space and time, and the challenges posted by Leibniz, in depth, it may be useful to formulate them in the language of modern physics. A common way to do that is to put Newton's absolute space and absolute time together in terms of Newtonian absolute spacetime, or simply Newtonian spacetime. Doing so can help us to visualise.

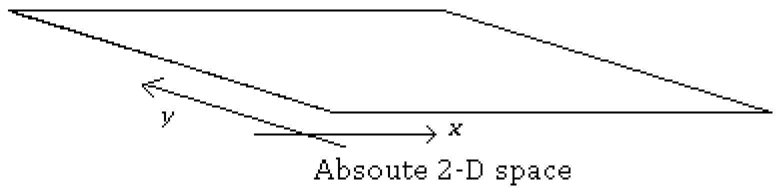

Figure-5.

As discussed above, Newtonian absolute space is an immovable and symmetric 3-dimensional Euclidean space, E^3 (Maudlin, 2012, p. 5). For simplicity, we can picture a static two-dimensional Euclidean space or, simply, a plane. Since it is an E^2 space, Cartesian coordinate system can help to add some metrical structure to Euclidean space. So, any point in the space can be represented by a pair of numbers, (x, y) (see figure-5). In Newtonian absolute space, since the notion of absolute motion is well defined, it is possible to picture a particle with some absolute speed moving uniformly and a particle at rest on a Euclidean plane.

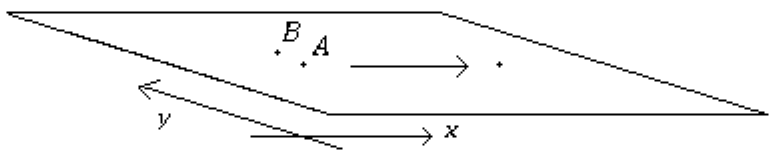

Figure-6.

Figure-6 shows that a free-particle, *A*, having absolute motion moving from one point to another point and a free-particle, *B*, remains as rest on an absolute plane.

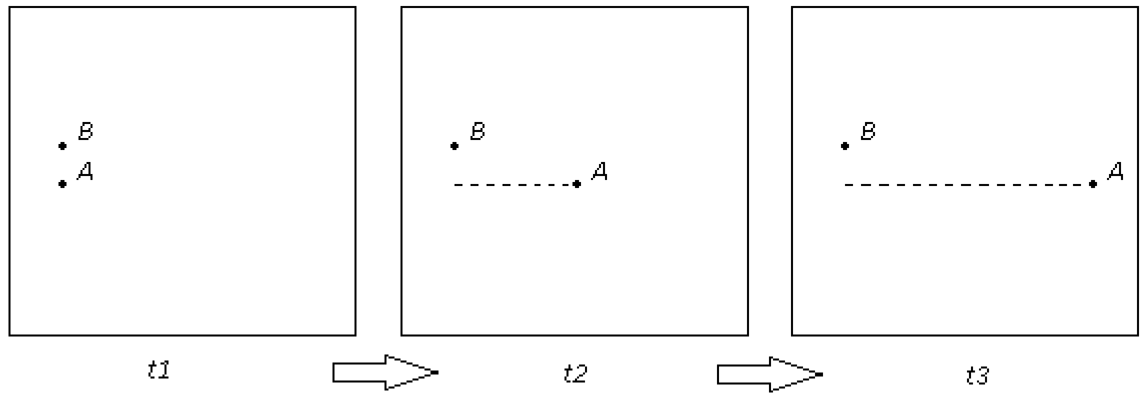

Figure-7.

In Figure-7, t_1, t_2 and t_3 represent different Euclidean planes at different moments. If each moment is stacked vertically in a chronological order, there will be what is commonly known as spacetime diagram (see figure-8). In spacetime diagram, there is a temporal dimension, other than spatial dimension. The t_1, t_2 and t_3 slices are the *instantaneous hyperplanes*.

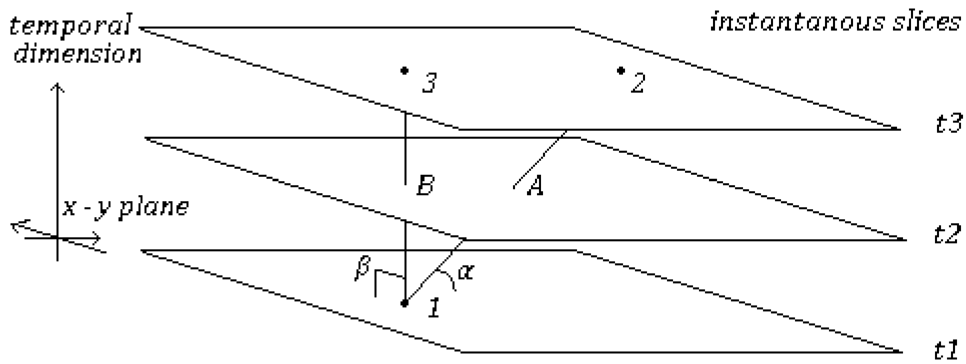

Figure-8.

One can imagine that these instantaneous hyperplanes are like taking photos during the period of the activity. If one chronologically stacks up all the photos taken, one will get the representation of spacetime. In Newtonian mechanics, it can also be called *simultaneous slices*, as simultaneity is absolute, so these slices record all the events that happened at the particular instance. The lines from point *1* to point *2* and point *1* to point *3* are traces or paths of particle *A* and particle *B* in spacetime, which is called a *worldline* or a *trajectory*. In

Newtonian spacetime, the worldline of a rest particle is orthogonal to the plane. Whereas, a uniformly moving particle will have an angle, α, other than right angle (see figure-8).

2.3 More on the Galilean Principle of Relativity

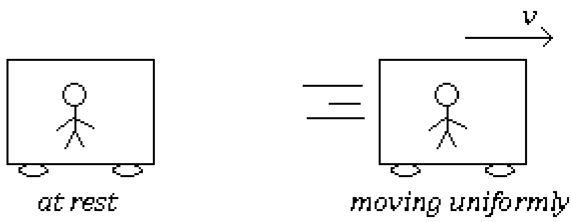

Figure-9.

Newton himself actually realises that his notions of absolute space and absolute motion are undetectable due to the Galilean Principle of Relativity. Galilean relativity has two possible readings, the Newtonian reading and Leibnizian reading. Galileo presents his principle with a ship example to show that motion is empirically undetectable. In this modern period, we will use a train as an example instead. Imagine that an observer is shut in a highly stable, steady and smooth enclosed train, with no windows. Galilean relativity says that there is no way for the observer, inside the enclosed train, to tell whether the train is *in motion* or *at rest*. There is no verifiable fact, like conducting experiments, whatsoever, to tell us what state of motion the train is actually in. Hence, the rest state and the uniformly moving state are physically and empirically indistinguishable in an enclosed train (see figure-9). Newton himself endorses this principle, which is stated in his Corollary V:

> *The motions of bodies included in a given space are the same among themselves, whether that space is at rest, or moves uniformly forwards in a right line without any circular motion* (Newton, 1729, p. 20)

The idea of absolute space is entrenched in the physics of Newton and Galileo in their days. When they formulate Galilean relativity, they make use of the notion of 'rest' and 'moving uniformly', as motion relative to absolute space. Despite the fact that Galilean relativity implies that rest and uniform motion are indiscernible, Galileo and Newton both agree that they are still two distinct states (Maudlin, 2012, p. 51). In short, the Newtonian reading of Galilean relativity (NGR) can be interpreted as:

> (NGR) *In either state, at rest or moving uniformly, the laws of motion are equivalent.*

On the other hand, there is Leibnizian, or relationalists', reading of Galilean relativity (LGR). It is a modern reading of Galilean relativity, as this reading does not involve the notion of absolute motion. Relationalists think that Galilean relativity implies something more than the indiscernibility between states of motion. With the help of Leibniz's shift argument, Galilean relativity also suggests that the absolute space is *redundant*, as Galilean relativity can be reformulated in term of *inertial frame of references*. Imagine that there are two trains, train *A* and train *B*, passing by each other with certain speed, *v*. By Galilean relativity, it is impossible to tell whether train *A* is actually moving or *B*. The observer in train *A* can regard himself as rest, so train *B* is moving with speed *v* to the right. Alternatively, the observer B may regard himself as rest, so train A is moving with speed *v* to the left. This reading makes use of the notion, *inertial frame of reference*. When observer *A* regards himself as rest, he is assigning an inertial frame of reference, *frame A*, which is at rest relative to himself. So, according to *frame A*, train *B* is moving with speed *v* to the right (see figure-10 right). Whereas, observer *B* can also regard his own train as rest by assigning himself a *frame B,* which is at rest relative to himself. So, in *frame B*, train *A* is moving uniformly to the left (see figure-10 left).

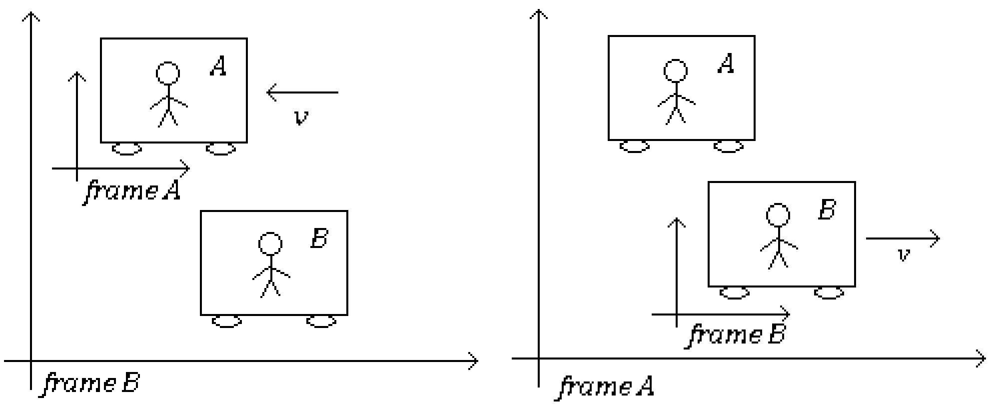

Figure-10.

In LGR, 'train *A* is moving' means nothing more than saying 'train *A* is moving with speed v in *frame B*'. In other words, there is a hidden concept in 'train *A* is moving', viz. train *A* is moving in frame *B*. The use of inertial frame of reference allows relationalists to talk about motion without referring to absolute space. When one wants to talk about motion meaningfully, one has to refer to frame of reference. In this reading, we can formalise Galilean Principle of Relativity as:

> (LGR) *In all inertial frames of reference, the laws of motion are equivalent.*

The Leibnizian reading of Galilean relativity does not involve absolute motion and absolute rest, like the Newtonian reading of Galilean relativity. This result becomes a weapon for relationalists to attack substantivalism.

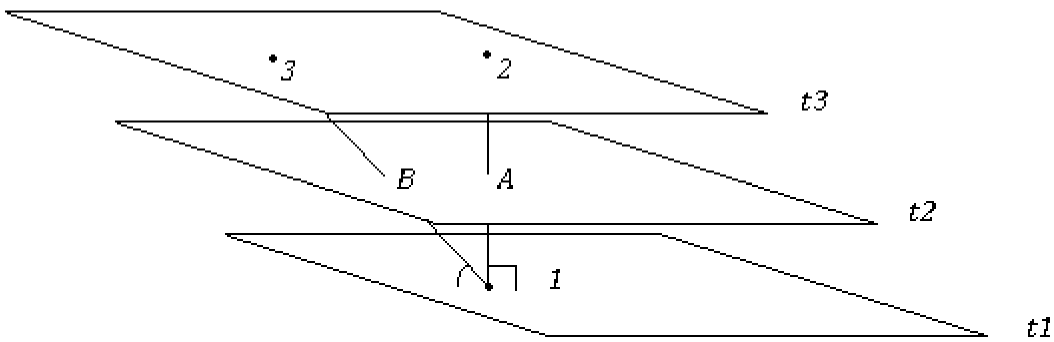

Figure-11.

Going back to the previous example, particle *A* moves uniformly from point *1* to point *2* and particle *B* endures at the same point in absolute space. Applying LGR, particle *A* is uniformly moving, with certain speed, in a certain direction, only in relation to a certain frame of reference. So is particle *B*, viz. it is at rest only because it is at rest in a particular frame of reference. Equivalently, particle *B* can be moving uniformly and particle *A* can be at rest if a different frame of reference is chosen (see figure-11). In this sense, the use of frame of reference allows us to assign arbitrary velocity to free-particle. Furthermore, the initial position of a free-particle is also only defined relative to a given frame of reference (see figure-12).

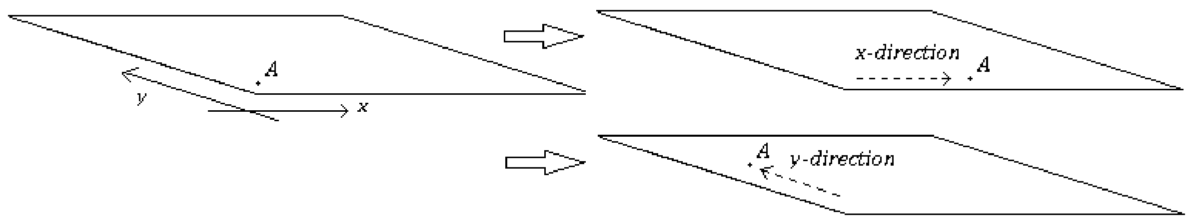

Figure-12.

In general, if we consider two inertial reference frames such that the second is moving at velocity *v* in the *x*-direction relative to the first, then the coordinates of an object in the first frame $\{x, y, t\}$, will be related to the coordinates of the object in the second frame $\{x', y', t'\}$, as follows:

$$x' = x - vt - x_0$$
$$y' = y - y_0$$
$$t' = t - t_0$$

Where x_0 and y_0 are the coordinates of the origin (0,0) of the second frame relative to the first frame and the time t_0 is the time 0 in the second frame relative to the first frame. This is called a *Galilean transformation*. Under the Galilean transformation, there are no absolute position and absolute velocity, as these two physical properties vary from reference frame to reference frame. Nevertheless, there are still some physical properties, which remain invariant under Galilean transformation, like the *distance* between two contemporaneous events, the time interval between two non-contemporaneous events, events that happen simultaneously and so on. These properties are called *Galilean invariances*, meaning that no *Galilean transformation* can change their value. Conversely, position and velocity are Galilean non-invariant.

The use of different inertial frames shows that there are different ways to stack up the time slices (see figure-8 and figure-11). For Newton, however, there is only one objective way to stack them due to how Newton postulates his absolute space, viz. space is immovable and static. Thus, the removal of absolute motion can be seen as a transition from *Newtonian spacetime* to *Galilean spacetime*.

Furthermore, Galilean spacetime also allows us to distinguish inertial motion from non-inertial motion. Non-inertial motions, like rotation and acceleration, are represented with curved trajectory, to distinguish with inertial trajectory, which is a straight line. In figure-13, particle *B* has a straight worldline, so it has an inertial motion; particle *A* has a curved worldline, so it has a non-inertial motion. In this way of representation, acceleration remains invariant, namely every inertial observer will agree with the value of acceleration.

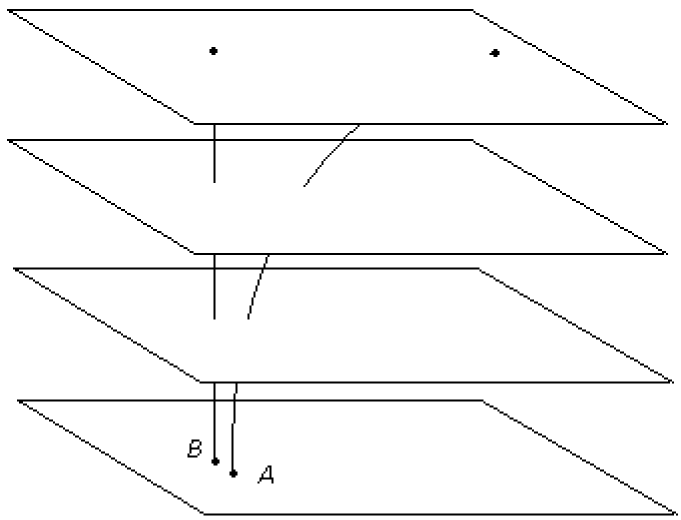

Figure-13.

Now, it should be clear that there are infinitely many different inertial frames, which can be assigned. For Newton, out of these infinitely many frames, there exists one frame, the privilege frame, which corresponds to his absolute space. Unfortunately, there is no way to know which frame it is, as the absolute space is unobservable. Newtonian absolute spacetime has a stronger structure than Galilean spacetime, as Newtonian absolute spacetime defines absolute states of motion. Whereas, Galilean spacetime manage to eliminate the notion of Newtonian absolute space and, from there, define relative velocity and relative position.

Chapter 3: The Relationalists' Return

In this chapter, I will focus on how relationalists can formulate Newton's mechanics without Newton absolute space. Then, I will bring out some modern physics theories, which are usually thought to be relationalists' theories.

3.1 Reformulating Newton's Mechanics

With the help of Galilean spacetime and geometry, Newton's first law can be reformulated in favour of relationalists in the following way:

> *Every body continues on a straight trajectory through space-time unless some force is impressed on it* (Maudlin, 2011, p. 37)

In the representation of Galilean spacetime, if a body's trajectory or worldline is straight, then the body is free from force. Equivalently, if a body is not free from force, namely the body is either accelerating or rotating (or simply non-inertial motion), the trajectory or worldline of the body is not straight, but curved, in Galilean spacetime.

The representation of the curved line in Galilean spacetime indicates non-inertial motion. Nonetheless, there remains one problem for relationalists, viz. acceleration is still absolute. Substantivalists can claim that acceleration is absolute because bodies accelerate relative to absolute space. To solve this problem, relationalists would need to explain what a body is relative to, when the body is accelerating. Lawrence Sklar (1974, p. 230) provides an answer for relationalists, that is to regard non-inertial motions as primitive. Sklar (1974) claims that non-inertial motions are not a relational motion. Saying '*x* is accelerating' is like saying 'apples are red' or 'sugars are sweet'. They do not need to be '*x* is red relative to something' or '*y* is sweet relative to something'. They are primitive terms. In my view, this is a reasonable price to pay. Newton's second law implies that when a body is impressed by force, the body is in non-inertial motion. In Newton's mechanics, force is real and statements, like '*x* is forced relative to something', do not make sense. In this case, I see no reason why non-inertial motions have to be relational. Therefore, relationalists can assert that non-inertial motions are primitive and they are represented as a curved line in Galilean spacetime.

With the relationalists' version of Newton's mechanics, substantivalism have faced another critique from relationalists in a modern physics standpoint. In the previous section, we have discussed how Leibniz's Shift thought experiments together with his two principles, PII and PSR, would work as arguments against Newtonian absolute space. Also, we have seen some possible defends for Newton. Now, regardless whether or not Leibniz's arguments still stand, there is new criticism. What truly fatal to Newtonian absolute space is the critiques from redundancy and undetectability, which are implied directly from the argument of non-invariance. As discussed before, the non-invariant quantities in Galilean spacetime are absolute velocity and absolute position, which are based on absolute space. Baker (2010, p. 1158) argues that the only real features in a given theory is its invariances. So, if *A* is not invariant in theory *T*, then *A* is not real in theory *T*. To be more specific, in a given theory, if certain features, which are not invariant in the theory, are postulated into the theory, the features are either *redundant* or *undetectable* (Dasgupta, 2015, p. 609). Since absolute velocity and absolute position are not invariant, there is no further reason to consider these notions and, therefore, absolute space. On the face of this argument, it may seem a bit too strong. After all, electrons are not observable, but they still work as a useful tool for doing physics. Unfortunately, relationalists do not agree that absolute space can be any useful to physics. The redundancy argument says that positing an absolute space is not necessary, when Newton's mechanics can still be a complete theory without the assumption of absolute space. Consider figure-8 and figure-11 again, these two figures represent the same situation. Galilean spacetime could not care less whether *A* is moving or *B* is moving. What really needs to be concerned in this case is the *rate of change of the distance* between *A* and *B*. If all the real quantities, the Galilean invariances, do not make use of absolute space, what use there is to postulate absolute space. Thus, absolute space becomes an 'extra' entity. More accurately, the notion of absolute space becomes *dispensable*. That is to say, when the absolute space is eliminated from Newton's mechanics, the theory becomes more attractive due to its simplicity, empirical success, unificatory power and so on (Colyvan, 2015). In fact, the dispensability of absolute space becomes even more so in the context of Einstein's special theory of relativity.

3.2 Einstein's Special Theory of Relativity

As discussed above, velocities are not invariant in Galilean relativity, meaning that the velocity of a particle depends on the inertial frame of reference being used. Thus, one can assign arbitrary velocity to a particle. Nevertheless, in modern physics, there is one exception in Galilean relativity, which is *the speed of light*.

In vacuum, the speed of light is constant for every inertial observer.

This principle is called the *Invariance of the Speed of Light Principle*, or simply the Light Principle. In other words, for two observers relatively moving to each other, regardless how fast they moving relative to each other, they both will measure the same speed of light emitting from a single source. The speed of light is commonly known as having the velocity *c*, which is approximately, $3*10^8$ m/s.

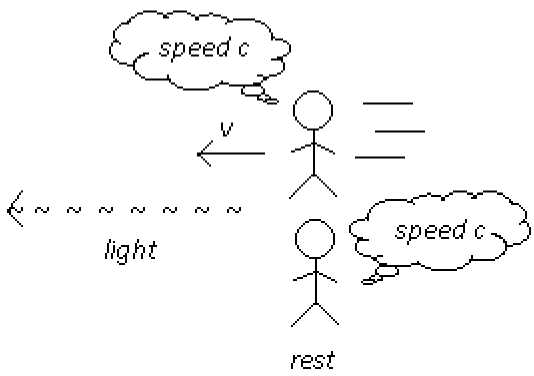

Figure-14.

At the first glance, it may strike one's attention that assigning a constant speed to light seems to suggest an absolute motion. It is not necessary the case. The essence of the Light Principle can be fully captured without the mention of the speed of light. Maudlin (2012, p.68) has provided a clear illustration to best understand this principle. Imagine that there are two sources of light, A and B, in a relative motion moving past each other (figure-15). Now consider an inertial frame of reference where B is at rest, when both sources of light pass each other, they will be triggered to emit laser beans in the same direction (figure-16). The Light Principle tells us that regardless how rapid the relative motion between two sources of light are, the laser beans, from both sources, will reach at the same point anywhere at the same time (figure-17).

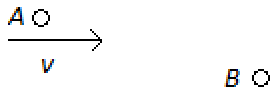

Figure-15.

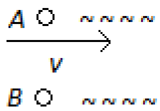

Figure-16.

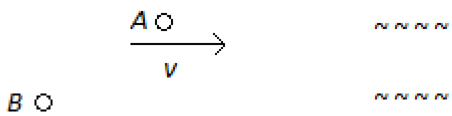

Figure-17.

This illustration tells us that the motion of light is independent of its source. In Einstein's own words, the Light Principle is '…the velocity of propagation of light cannot depend on the velocity of motion of the body emitting the light (Einstein 1961)'. Now, when Galilean Principle of Relativity and Light Principle come together, Galilean transformation becomes problematic, as the speed of light does not vary from reference frame to reference frame. Instead, the correct transformation here is *Lorentz transformation*. Transforming from one frame (x', y', z', t') to another (x, y, z, t),

$$x = \frac{x'}{\gamma}$$

$$y = y'$$

$$z = z'$$

$$t = \gamma t'$$

Where $\gamma = 1/\sqrt{1-\frac{v^2}{c^2}}$. As I pointed out in the previous section, Newton's mechanics uses Galilean spacetime, with Euclidean space structure. Whereas, Einstein's special relativity uses *Minkowski spactime*, with Euclidean space structure. When the geometry is concerned, Galilean spacetime and Minkowski spacetime works well in Cartesian coordinate and in Lorentz coordinate, respectively (Maudlin, 2012, p. 69).

3.3 Minkowski Spacetime

The 3-diemsional spacetime diagram of Minkowski is this:

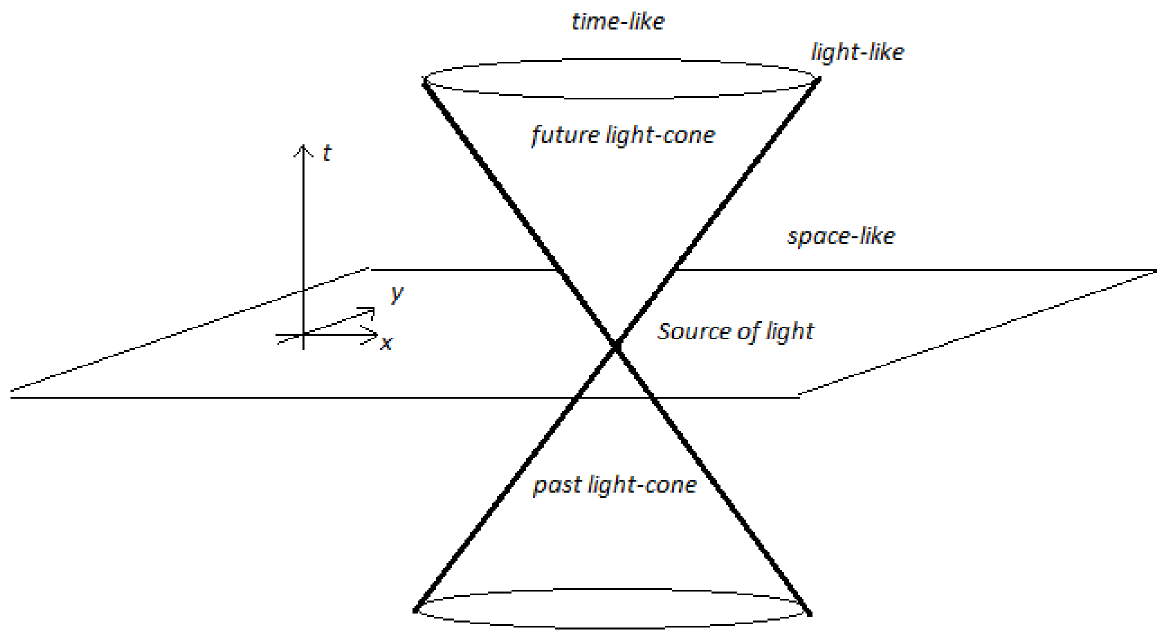

Figure-18.

The cone in the middle is called light-cone. It can be imagined as an exploding event, which then emits light. As time passes, the light expands equidistantly and, hence, forms a circle. From the perspective of spacetime, it can be seen as a cone. The trajectory which the light traces is called light-like path or null-path. Any events lie inside the future light cone is said to have time-like trajectory and events lie outside the light-cone is said to have space-like trajectory. For convenient purposes, a 2-dimensions spacetime diagram will help to illustrate Lorentz transformation.

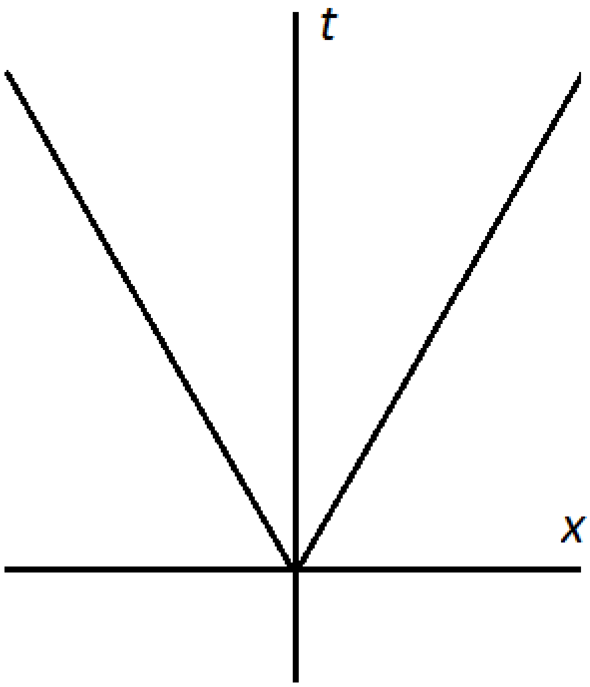

Figure-19.

The trajectory between x-axis and t-axis is the light-like path. According to the Light principle, the propagation of the light is the same for every inertial observer. So, when the Lorentz transformation is performed, the light-like path should remain invariant. Thus, we have this:

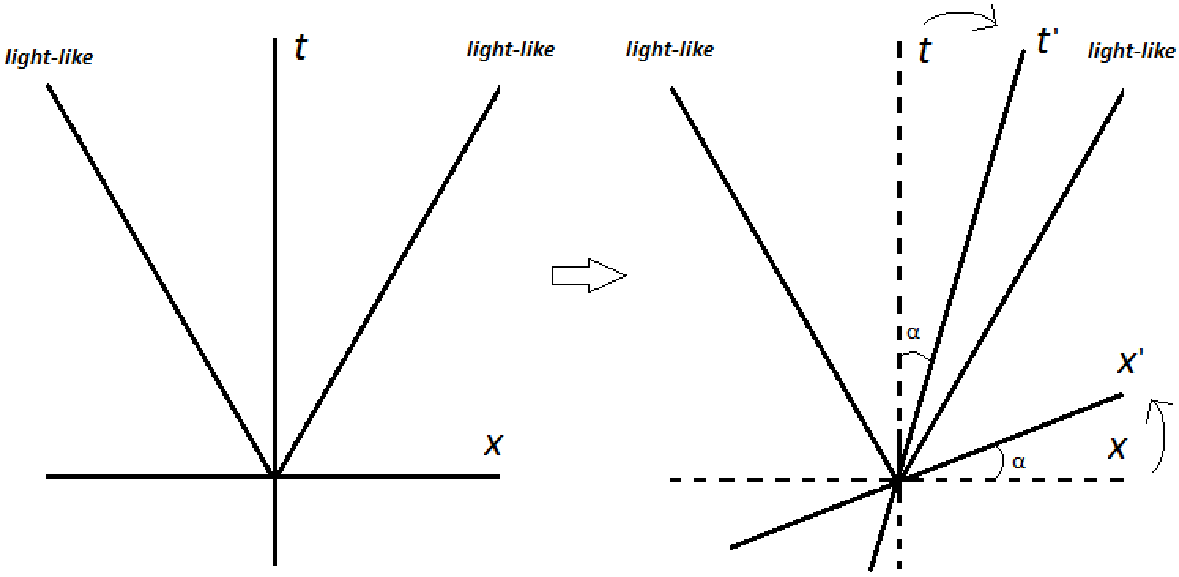

Figure-20.

The marriage of the Light Principle and Galilean relativity gives birth to one of the most prominent theories, Einstein's special theory of relativity. Special relativity is normally regarded as a relationalists' theory, meaning that special relativity works better in relationalists' framework than in substantivalists' ones. This is mainly due to the phenomenon derived from special relativity, such as *length contraction*, *time dilation* and *relativity of simultaneity*.

As we have discussed in previous section, the invariances in Galilean transformation are the distance between two contemporaneous events and the interval between two non-contemporaneous spacetime points; whereas the non-invariances are the velocities and positions. However, in Lorentz transformation, neither the spatial or temporal interval between spacetime points are invariant. In spatial dimension, spatial distance between two points is no longer absolute, as it depends on the observer or, more precisely, inertial frame of references, which measures it.

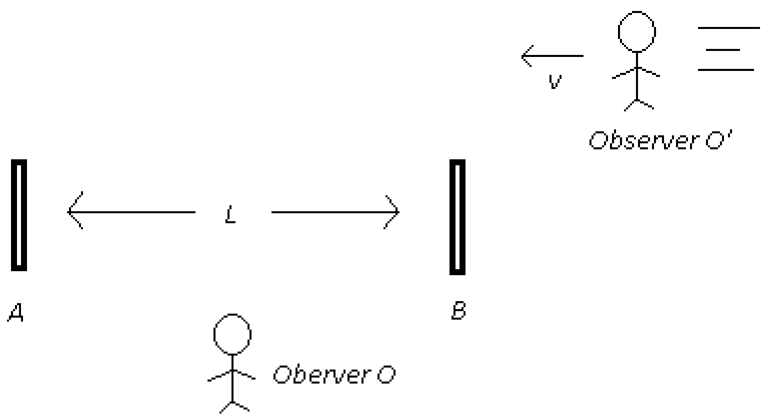

Figure-21.

In this case, there are two observers *O'* and *O*, who are in uniform motion, *v*, and at rest relative to the poles, respectively (consider the relative motion is great). According to special relativity, the spatial distance between pole *A* and pole *B* will 'appear' to be shorter in the measure of observer *O'* than in the measure of observer *O*. In other words, the value *L* in the measure of the rest observer is greater than the moving observer. The same effect goes to the temporal case. In this case, observer *O'* measures the time he, himself, takes from pole *B* to pole *A*, say he measures *t'*. Meanwhile, observer *O* measures the time observer *O′* takes from pole *B* to pole *A*, say he measure *t*. Although both observers measure the same event, their results are different. In this situation, the value of *t′* is less than the value of *t*. In other words, the time of the observer *O′* will 'appear' to be slower than the observer *O*. Now, imagine two lightings, which strikes at the poles, *A* and *B*. For observer *O*, he measures or sees the two lightings striking simultaneously at pole *A* and pole *B*. However, for observer *O′*, he sees one lighting, which strikes at pole *B* first, then he sees another lighting, which strikes at pole *A*. For observer *O′*, the lightings do not happen simultaneously.

One may ask questions like, 'what is the real distance between pole *A* and pole *B*', 'how long does the observer *O′* take from pole *A* to pole *B*' or 'does the lightings really happen simultaneously'. In special relativity, these questions are meaningless, as there is no objective time and objective space. Hence, there is no real distance or true interval. The objective metrical structure of space and time in Newton's mechanics is replaced by clock and ruler in Einstein's special relativity. What this means is that space and time depend on the observer's clock and ruler, who measures it. More precisely, the metrical structure becomes frame-dependent. There is no 'true' distance, but only distance relative to inertial frame.

Minkowski spacetime is a great tool to illustrate the relativistic effects. Take the relativity of simultaneity as an example. In frame *O* where observer *O* is at rest relative to the frame, observer *O* saw two lightings struck at pole *A* and pole *B* simultaneously (see figure-22). In frame *O′* where observer *O′* is at rest relative to, observer *O′* saw the lightings struck at pole *B* first then pole *A*. This is not to say that observer *O′* has an inaccurate measurement, as we can construct another representation of Minkowski spacetime on the same case (see figure-23). The outcome is the same, where observer *O*′ saw two lightings non-simultaneously and observer *O* saw them simultaneously.

The quantities, which regard as invariances in Galilean spacetime, now becomes relative in Minkowski spacetime. Distance between contemporaneous events, interval between non-contemporaneous events and absolute simultaneity all become frame-dependent and non-invariant. If we were to follow what Baker claims, viz. the only real features in a given theory is its invariance, then we would need to exclude distance, duration and absolute simultaneity. This result is advantageous to relationalists because even the notions of distances, durations and simultaneity depends on the observers.

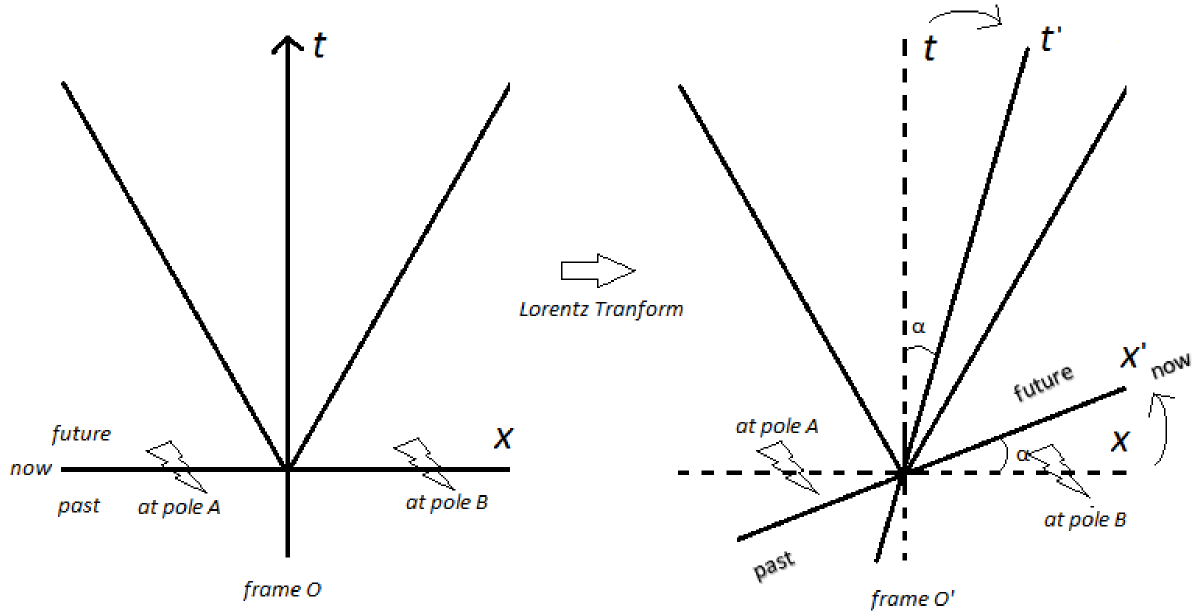

Figure-22.

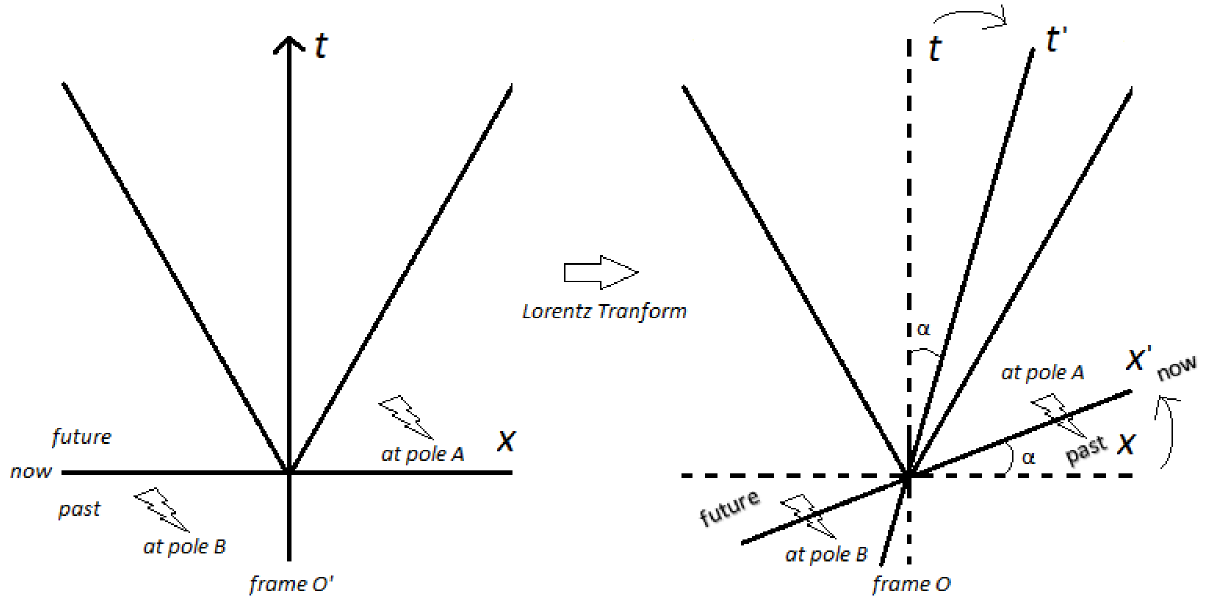

Figure-23.

Chapter 4: The Study of Metaphysics and the Study of Science

This chapter is a preparation for my latter argument. In this chapter, we look at the essence of the debate between substantivalism and relationalism. This is important, as it helps us to understand in what aspect they are actually in odds.

4.1 The Nature of the Debate: Why Are They at Odds

Surprisingly, in many aspects, substantivalism and relationalism are very much alike. In the example of Newton and Leibniz debate, Newton and Leibniz both agree that motion is only meaningful if it is understood in term of relative motion; there is no physical change if the universe is shifted statically or kinematically; in some sense, space is not a substance (Earman, 1989, p. 111). However, the difference is that, in term of ontology, substantivalists go one step further, posting a substantial space, as an independent existence, which relationalists regard as extra and redundant entity.

4.2 The Compatibility between Substantivalism and Relationalism

In my view, the way relationalists handle substantivalists today is different from how Leibniz handles Newton. Leibniz directly attacks on the metaphysical and ontological status of absolute space. Whereas, the redundancy and undetectability arguments from relationists are more like how science in general should be done. In Babour's remark (1982, p. 251), science in general is only possible when variety can be perceived. Analogically, positing absolute space is like positing colour properties or taste properties to electrons, 'what is the colour of an electron?' or 'what does an electron taste like?'. These properties are extra entities. They are redundant because, regardless what the taste or colour of electrons is, it will not affect any physics theory whatsoever. Besides, they are undetectable. So, the argument becomes 'why do we need to talk about such things' instead of directly answering the questions, 'whether or not electrons do have taste'. Thus, the redundancy and undetectability argument avoid answering the question 'is there a space', instead they take a different route arguing that the notion of space is useless. Now, I think that if substantivalists were to force relationalists to answer the question, 'is there a space' directly and explicitly, the relationalists' answer is neither yes nor no. In this case, one can clearly see that substantivalists and relationalists are taking stands at different levels.

Substantivalists are arguing from a metaphysical perspective, whereas relationalists are arguing from a 'how-physics-as-a-science-should-be-conducted' perspective.

I stress that this distinction is crucially important, as it gives some insights about the essence of the argument between substantivalists and relationalists. I believe that this distinction shows two different levels of arguments between substantivalism and relationalism. One is from the perspective of ontology, as the study of metaphysics and another is from the perspective of physics, as the study of science. As I have stated in above section, in the central claims of relationalism and substantivalism, relationalists claim that space has no independent existence, but only a set of relations among objects. On the other hand, substantivalists claim that space is substantial, namely it has independent existence, and the nature of space is not a set of relations among objects. These claims are about the nature of space, what space *is* and what space *is not*. In my view, the introduction of the redundancy and undetectability argument divides the debate between substantivalism and relationalism into two levels, metaphysics and science. The nature of space belongs to the study of metaphysics or ontology. Now, if what I have argued above is true, then substantivalists and relationalists are not necessary in a disagreement. Substantivalists can agree with relationalists that substantial space is unobservable and only relations among objects can be observed. So, it is reasonable that when one does physics, as a subject of science, one works with relations. Nonetheless, once ontology is considered, substantial space must be in the list. The same goes to relationalism. Relationalists take no opinion in the ontology of space. Hence, it implies that relationalists are not at odds with substantivalism. In this sense, substantivalism and relationalism are, in fact, compatible. Of course, this view is only true in the context redundancy and undetectability argument. That is if relationalists insist on remaining on the level of redundancy and undetectability argument, then relationalists and substantivalists are compatible.

In reply, relationalists may argue that they see no reason why physics should go into the area of metaphysics. Granting that the questions about the taste and the colour of electrons can be answered, one would probably say 'cool, that is interesting. Now what? What can the taste and the colour of electrons possibly imply?' Regardless whether or not substantivalists have a complete theory about the nature of space, since physics theories can still be complete and successful without substantial space, there is no reason why we should not dispense with substantial space. If substantivalists insist that the study of the nature of space remains on the level of metaphysics, it seems like substantivalists have nothing to contribute to physics, as the study of science.

Chapter 5: Standing for Substantivalism

Having differentiated two levels of arguments between substantivalists and relationalists, I think it is necessary to argue for substantial space individually. In this chapter, I will consider two levels of arguments for substantivalism. One is from the perspective of physics, as the study of science. Another is from the perspective of ontology, as the study of metaphysics. Then, I will conclude that, either in physics or ontology, the notion of space is indispensable.

5.1 Physics, as the Study of Science

In the physics argument, I will first talk about what it is for something to count as a substantial space. Once clarified, we are in a better position, knowing how to argue for substantivalism. We then look into some physics theories to discuss whether or not there is an embedded notion of substantial space.

5.1.1 Answering the Question again: What is Substantial Space?

For substantivalists to come back into the battlefield of physics, they need to make the notion of substantial space 'useful', otherwise they will always remain in the realm of metaphysics. As Disalle (1994, p. 272) puts it, the only observables are the spatial relations. For space and time, they are regarded as theoretical entities. To believe the existence of space, further justification is required. Like electrons, space cannot be directly observed. Unlike electrons, the evidence or the justification of space is not as strong as electrons.

I do agree with Earman (1970, p.288) that, when one argues for or against absolute space, what does one really argue? In other words, what is the absoluteness in absolute space? The same goes to substantial space. It seems to me that one will need to solve this problem before one can actually argue for or against absolute space.

There is a necessary condition for which every version of substantivalism must hold. *To think of a substantial space is to think of a space, as an independent existence*. That is the minimal substantivalists's claim. Newtonian absolute space is a kind of substantial space. However, it is important to note that there are distinctions between substantial space and Newtonian absolute space. Absolute velocity and absolute position are well-defined in Newtonian absolute space. However, substantial space does not necessarily allow the notions of absolute velocity and absolute position. Newton believes that, out of the infinitely many inertial frame of reference, there is a privileged frame which corresponds to absolute space. Whereas, a substantial space may not imply that. Newtonian absolute space may fail in the modern context, but substantial space may not.

Now, we may ask the question what it is for something to count as real or independent existence. For this question, the Eleatic Principle can give us an answer.

5.1.2 Eleatic Principle

The Eleatic Principle is a principle of ontology, which says that only real entities can affect or be affected. In a formal language, the Eleatic Principle is this:

> An entity is to be counted as real if and only if it is capable of participating in casual process (Colyvan, 1998, p. 2)

There are two directions in Eleatic Principle, the *if* direction and the *only-if* direction. The *only-if* direction is controversial, as there are some real entities, which seem to lack of casual process. This usually happens in the context of philosophy of mathematics, as Mathematical Platonists think that numbers are real, yet having no causal interaction. Conversely, the *if* direction is fairly uncontentious. Philosophers, like Hartry Field (1989), David Armstrong (1978), Brian Ellis (1990) and Mark Colyvan (1998), generally agree that casual activity is a sufficient criterion for something to be real. For the purpose of my argument, I will take the *if* direction in Eleatic Principle for granted. If I am right, then we have a reason to believe that if space is capable of participating in casual process, then space can be counted as real entity.

Now, back to our space argument, to follow Eleatic Principle, substantial space needs to be richer than just being idle. It must be able to do 'something'. In this sense, space, as an independent existence, can be taken to mean that *it can act and can be acted upon*. In turn, to say that space can act and can be acted upon is to say that there are some observable features of space, which is able to interact with things in the universe. Hence, we acquire the existence of space through the features, properties and structures it has, if it has at all. Analogically, imagine that there is a table in front of us and we are told that there is an invisible container on the table. To find out more about the invisible container, we can pour some liquid on the table, to locate where about the container is; we fill the container up with water, to find out the shape of the container; we can put some colour solution into the water to see how the container interact with colours; and so on. Despite the fact that the container itself is not observable, we can still study the structure of the container. Therefore, I propose that substantivalists should look for the structure of space.

5.1.3 The Invariance of the Speed of Light

Many absolute notions in classical mechanics have become relational in modern mechanics, especially in Einstein's special relativity. Special relativity is widely regarded as the relationalists' theory, as it works better in the relationalists' framework. However, I shall argue that, this does not mean that relationalists have managed to develop a theory without a substantial space. In fact, if we look closely enough, we can find some elements of substantial space in special relativity, as Minkowski spacetime seems to suggest an objective structure of spacetime. To see the embedded notion of substantial space, it is necessary to look deeper into the Light Principle.

As discussed above, special relativity is based on two postulations, Galilean Relativity and Light Principle. However, there are papers, for examples David Mermin (1984), Achin Sen (1994), Vittorio Berzi and Vittorio Gorini (1969), Andrea Pelissetto and Massimo Testa (2015), etc. arguing that Lorentz transformation can be obtained by considering only Galilean Relativity with few basic assumptions, but no assumption of Light Principle. In other words, special relativity might not necessarily depend on the assumption that the speed of light is constant for all inertial frames (Nerlich 2010). For Hermann Minkowski, the process to obtain special theory of relativity is just purely mathematical. The way Minkowski derives Lorentz transformation differs from Einstein, as Minkowski did not assume Light Principle (Nerlich, 2010).

Minkowski thinks that space and time are closely related. So, he attempts to combine two symmetries in Newton's mechanics into one (Nerlich, 2010). The two symmetries are the translational symmetry (the characteristic of Euclidean space) and the velocity symmetry (Galilean relativity), which are related to space and time respectively. In attempting to do so, Minkowski comes to the equation of spacetime interval, which is the heart of special relativity:

1. $ds^2 = cdt^2 - dx^2 - dy^2 - dz^2$

The parameter *c* is introduced to help combining the two different types of symmetry together. This, in turn, gives us a form of *Lorentz transformation*, with no specific value of *c*. This result is significant as no light or electromagnetism is mentioned whatsoever (Nerlich, 2010).

If we can derive Lorentz transformation without the Light Principle, then the parameter *c* *per se* in Lorentz transformation suggest that *c* has nothing to do with light and electromagnetic waves. Now, my concern is that what does *c* itself amount to? In my view, the parameter *c* implies that there is an 'objective' upper speed limit. If this is so, then the notion of relative speed may not be so 'relative' after all, as there is a sense of *objectivity* in speed. 'So what?' a relationalist may defend 'this objectivity does not further infer anything more than just 'in any inertial frame, nothing can go beyond this speed *c*''. However, I shall argue that the parameter *c* says more than that. It actually entails the objective structure of spacetime. My particular concern is the parameter *c*.

5.1.4 The Objective Structure of the Minkowski Spacetime

Consider again the Minkowski spacetime diagram (see figure-19), the line between the x-axis and t-axis is the light-trajectory, light-like path or null-path. It is the path in spacetime where the light traces. Under Lorentz transformation, the x-axis and t-axis will be tilted with certain degree, but the light-like path remains the same because, according to Light Principle, the speed of light is the same for every inertial frame. So, the speed of light remains invariant (see figure-20). In this interpretation, relationalists can argue for themselves that the speed of light only make sense when inertial frames of reference are used, e.g. the speed of light is *c* relative to all reference frames. When the reference frames are absent, there is no objective speed of light, as one cannot even talk about speed. Indeed, I do agree that 'the speed of light is the same for every inertial frame', 'the speed of light is *c*', 'the speed of light is invariant' etc. are only meaningful when the coordinates or inertial frames of reference are presented. However, as argued before, both speed of light and light have nothing to do with the parameter *c* in Lorentz transformation and in Minkowski spacetime because the absent of Light Principle will not affect us to derive Lorentz transformation. If this is true, then what is the explanation for the invariant characteristic of the null-path. That is, why does the null-path remain invariant under Lorentz transformation, if we do not have Light Principle to explain it. It seems to me that the only explanation for this is to appeal to the objective structure of Minkowski spacetime.

To give a full account, we need a new interpretation, called the frame-free interpretation, where no coordinate and inertial frame of reference will be used. In this interpretation, the concept of speed, the invariance of light and so on are not well defined (Nerlich, 1982, p. 365). Now that this interpretation has no Light Principle, the parameter *c* is no longer defined as the speed of light. What does *c* in the equation of spacetime interval (equation 1. above) amount to then? I argue that it serves the function of structuring spacetime. It defines the null geodesics. *That is when the light is introduced, it is the path which the light will and must lie. In other word, the speed of light does not determine the parameter c. Instead, it is the parameter c which determines the trajectory of light in Minkowski spacetime*. So, when a reference frame is brought into the picture, the parameter *c* defines light speed. This parameter *c*, or the speed limit, is the structure of spacetime, which is represented by Minkowski spacetime. One can imagine that the Minkowski spacetime is like a basic framework, or skeleton, of spacetime.

There are two interpretations presented to us, the conventional interpretation and the frame-free interpretation[4]. I am not claiming that the conventional interpretation is false. The conventional interpretation, though conventional and straightforward, is not a good interpretation because it gives the misunderstanding that the null-path depends on the notion of light and light is special, when clearly it is not the case. The frame-free interpretation, on the other hand, is more elegant in the sense that it has only one postulation and it does not give the misconception that light is special. The trajectory of light just follows the objective structure of Minkowski spacetime. This interpretation can be put in this way: 'Minkowski spacetime has some sort of objective structures, such that all the matters, objects and physical entities must follow these objective structures.'

[4] The conventional interpretation and the frame-free interpretation are what Nerlich (Nerlich, 1982, p. 365) calls the *relativity interpretation* and the *spacetime interpretation* respectively.

5.1.5 Seeing Space in Physics Theories

DiSalle (1994, p. 273) rightly points out that philosophers and physicists are so used to the notion of spatiotemporal relations in virtues of their own and they often overlook the underlying structure of the geometry. There are many concepts in physics, which make use of the notion of substantial space without knowing. One example is the qualities in space. This challenge is posed by Field (1984, p. 50). Consider two statements, 'the distance from particle A to particle B is the same as from particle C to particle D' and 'the distance from particle A to particle B is twice as far as from particle C to particle D'. Let the first statement be $AB * CD$ and the second statement be $AB *_2 CD$, the question is 'what is it for something to be twice as far?' One reasonable answer can be expressed as follow:

$$(AB *_2 CD) \leftrightarrow \exists u: ((Au * uB) \wedge (uB * CD))$$

In other words, 'the distance from particle A to particle B is twice as far as from particle C to particle D' means that there exists a point, *u*, in between particle A and particle B such that the distance from particle A to *u* and from *u* to particle B is the same as the distance from *u* to particle B and from particle C to particle D. However, this answer only works in a substantivalists' framework as the formula above uses 'there exists a point *u*'. For substantivalists, they can assert a point existing in space even though there is no particle at point *u*. Yet, for relationalists, there is no point existing in space, as such a point is an abstract entity and no relation can form with abstract point (Field, 1984, p. 52).

I shall point out another concept, which I find relationalists fail to formulate it without substantial space, namely the concept of geodesic. The concept of geodesic path is widely used in Newton's mechanics and especially in Einstein's general relativity. In order to make sense of this concept, it seems to me that it will need to draw the notion of substantial space.

In Newton's mechanics, even though the notion of absolute state of motions can be dispensed, the geometric structure between inertial motion and non-inertial motion cannot. To construct a geometry of space which is able to distinguish between inertial motion and non-inertial motion, the geometry needs to presuppose certain objective structure of space (Maudlin 2012, p.33). In the relationalists' formulation of Newton's first law, the notion of straight line depends on the *affine structure* of space. In other words, if a space is able to distinguish curved line from straight line, it means that the geometrical structure of space involves affine structure (Maudlin 2012, p.32).

Furthermore, in the context of Einstein's general relativity, the trajectory of every inertial body has to follow the structure of spacetime too. In Newton's mechanics, the phenomenon, the earth rotating around the sun, is explained by gravitational force, namely the force of the sun 'pulls' the earth and, hence, it forms the rotational motion. Whereas, in Einstein's general relativity, this phenomenon is explained by geometry of spacetime, namely the mass of the sun curves the geometry of spacetime, in such a way that the earth moves inertially according to the curvature of spacetime and, hence, the earth forms a 'rotational motion'[5]. The path, which the earth follows, is called a geodesic path. A geodesic path is a shortest path between two points in spacetime. Also, it is the paths which every inertial object must follow (Norton 2015). So, in a flat spacetime E^3, a geodesic path is a straight line. This explains why, in Newton's mechanics, a free-particle follows in a straight line in spacetime. In a non-Euclidean spacetime, a geodesic path is best explained as the shortest possible path between two points, which is locally a straight line. Now, the use of geodesic path in general relativity is closely related to the structure of spacetime. As Norton (2015) points out, a massive object, like the sun, curves the fabric of spacetime, which consequently causes the change of the geodesic path in that region. If general relativity is understood in this way, then we have a reason to believe that a free-particle actually moves in spacetime and the trajectory of the particle is influenced by the curvature of spacetime that is the structure of spacetime.

> *Space acts on matter, telling it how to move. In turn, matter reacts back on space, telling it how to curve* (Misner et al., 1973)

I believe that general relativity works as a good example on how space can act and can be acted upon.

There are many seemingly minor issues, which relationalists gives no explanation and takes for granted. Consider a situation where there are two particles traveling and getting closer.

[5] It is not entirely rotational motion. In the perspective of the earth, or locally, the earth is moving in a straight line.

Eventually, they intersect with each other and they move away from one another without getting second intersection.

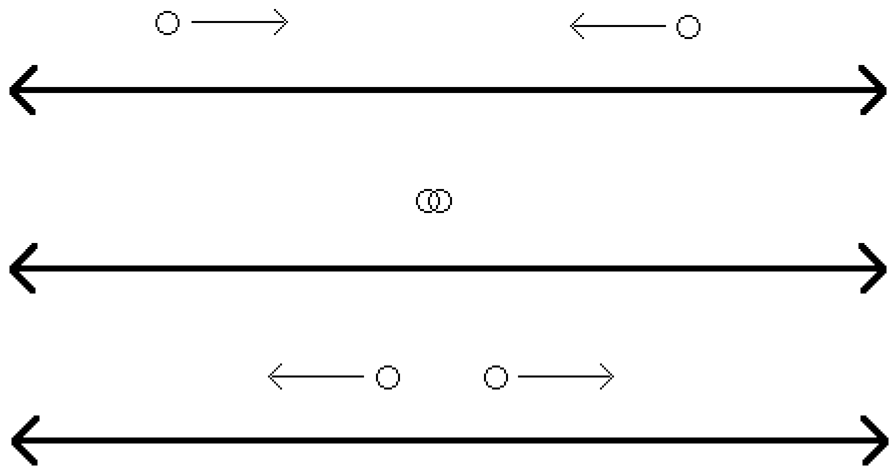

Figure-24.

One question can be asked is that 'why they intersect only once?' To answer this question, substantivalists can appeal to the structure of space, namely there is an objective structure of space where everything in the universe has to follow. In this sense, the answer lies in the affine structure of a flat Euclidean space, where the particles can only intersect once, and then they get further and further apart. Equivalently, if the situation is that the particles intersect regularly while both traveling in opposite directions, the substantivalists can, too, appeal to the structure of space. It may be the case that the space has circular manifold.

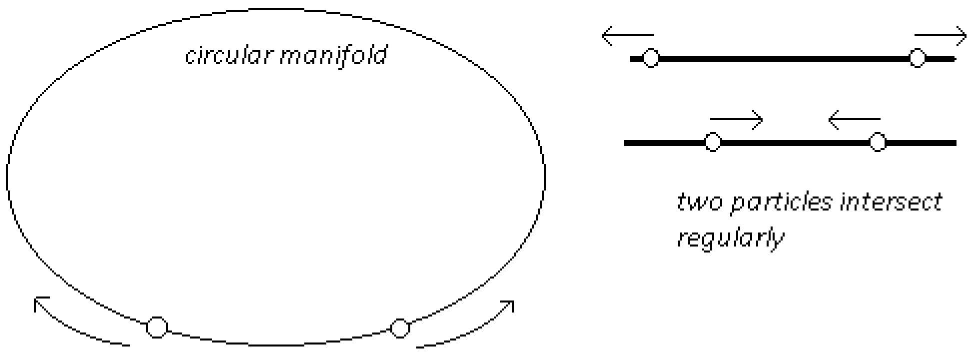

Figure-25.

5.1.6 Relationalists have Something to Say

In response, relationalists can take Sklar's argument:

> *'Insofar as talk about spatiality is meaningful, the relationalist alleges, it is talk about the spatial relations born to one another by the point material objects of the idealization. To view it as talk about 'the structure of space itself' is to wallow in metaphysical confusion.'* (Sklar, 1974, p. 168)

By spatiality, Sklar means that the things which make spatial relations possible. Take the circular manifold as an example, relationalists may say that the spatial relation between two free-particles cannot be greater than certain value. Once the distance between two free-particles exceed the value, the two particles will behave strangely, such as they will suddenly move in an opposite direction. Relationalists make use of the notion spatial relation between two free-particles. In this example, the spatiality between the two free-particles is what makes the spatial relations possible, namely there is certain value in distance which the two particles cannot exceed. For the problem of geodesic, relationalists may try to reply that the reason why inertial bodies follow geodesic paths is not because they follow the geodesic paths of spacetime, but because of the laws of geodesic, viz. a free-particle just moves according to the law of geodesic:

$$\frac{d^2x^\mu}{ds^2} = -\Gamma^\mu_{\alpha\beta}\frac{dx^\alpha}{ds}\frac{dx^\beta}{ds}$$

In the example of the earth rotating around the sun, relationalists will deny that the earth is following the geodesic path of the spacetime, which, in turn, is curved by the sun. Instead, they say that it is just the spatial relations between the earth and the sun and the spatiality is the law of geodesic. As long as the talks about spatiality do not involve the notion of space or spacetime, it is a meaningful talk (Sklar 1974, p.167).

> *'Actually, such attempts to define the 'spatiality' of spatial relations are usually taken as ineffective if not unintelligible, so I shall simply give to the relationalists his designated family of relations: spatial, temporal, or spatiotemporal, as the need may be'* (Sklar 1974, p.169)

However, it seems like one can still ask questions, like 'why the distance relations between two free-particles has certain limited value' or 'what does this geodesic equation really refer to'. The way Sklar and other relationalists handle these cases is to call for a stop and regard these questions as nonsensical nonsensical. There is no need to give any further explanation.

In my view, the way relationalists handle these cases are not very satisfying and convincing. What relationalists are doing is simply describe how the nature works. As Hoefer (1998, p. 466) himself remarks that *'equations without interpretation do not constitute fully successful physics, even if the equations are connected to successful experimental prediction'*. After all, it seems reasonable that we can go deep down into the fundamental.

5.1.6.1 PSR Interlude

At this moment, I would like pause for a while to bring in Leibniz' Principle of Sufficient Reason into the play. The following is the outline of my argument:

1. PSR is actually a principle for substantivalism.
2. The argument against PSR is the argument for relationalism

As I mentioned above, if we can dismiss the flaw in PSR, PSR is actually in favors of substantivalism. Consider this, if PSR were to be true, then it means that there must be reasons for why things are the way they are, including why the spatial relations are the they are. So, there must be an explanation for the nature of spatiality. If this is the case, relationalists are out of the game of science because relationalists simply are not in the position to give such a reason[6]. They refuse to give reasons and explanation for their results. On the other hand, substantivalists are willing to take the job of explaining, by appealing to the notion of substantial space.

Unfortunately, for my honest thought, the PSR is too weak, in the sense that PSR is unlikely to be true. As I have argued above, it is unlikely that everything has a reason for their existence. At some point of enquiries for reason, it must either be self-caused or endless enquiries. In either case, there must be again a reason for why it is self-caused or why the

[6] Consider science has the duty to explain, other than predict.

enquiries are endless. The argument against PSR becomes the argument for relationalists. If the enquiries must stop at some point, the relationalists may be right on stopping at that point, viz. they refuse to give any further reasons for the nature of spatiality. So, relationalists can appeal to the argument, which is used to against PSR.

Now, despite that there is a reason to stop somewhere in the enquiries, the question becomes where is the good point stop? Here, again, we face two levels of argument. Should we stop at the descriptive part or should we go beyond the descriptive? That is should we go on to posit space, which seems to provide reasonably good explanation for our current science, or is it too luxurious to ask for explanation? Well, I think we should for the notion of space. I agree with Hoefer (Hoefer, 1998, p. 463) that the argument between substantivalism and relationalism cannot only be in the context of a given theory. Rather, it should be in the context of all our current knowledge of and assumption about the world. That is, physics cannot remain only at the level of science, but it should go beyond the science to the study of metaphysics.

5.2 Ontology, as the Study of Metaphysics

In this section, we will look at space from the perspective of metaphysics. Firstly, we will discuss the relations between conceivability and possibility. I will argue that logical inconceivability entails logical impossibility. Then, I argue that the state of spacelessness is inconceivable. Hence, spacelessness is logical impossible.

5.2.1 Conceivability and Possibility

Apart from physics, even in the study of metaphysics, substantial space is indispensable. The idea that space is nothing but only relations is actually impossible from the standpoint of metaphysics and phenomenology. It further implies that there must be an extra structure for space, namely the substance-ness of space.

Relationalists have been holding the idea that there is no space but only sets of relations among observable objects. However, there is no serious and careful examination about whether or not the concept of spacelessness is actually possible. This examination is a necessary one, as one does not simply go out to drill a hole into the centre of the earth to find an underground kingdom. A careful study of the earth will give us the answer that there is no underground kingdom in the centre of the earth, as the temperature, pressure and other factors shows the physical impossibility. In my view, the same examination should be done to the concept of spacelessness.

Knowing whether or not something is possible has to do with conceivability. The philosophical discussion of relations between possibility and conceivability has a long history. There are two principles in this regard (Lightner, 1997, p. 115). One is Conceivability Principle:

If A is conceivable, then A is possible

Another is Inconceivability Principle:

If A is inconceivable, then A is impossible

At the first glance, these principles are not plausible, as one can think of some cases which shows that they are false. For the Conceivability Principle, I can imagine something moving faster than light, yet it is impossible[7]. For the Inconceivability Principle, I cannot imagine a colour that is entirely new to the mankind, yet it is possible that such colour exists.

It is not the case that these principles are wrong. We just need to be more careful on formulating the principles. In a thorough formulation, possibility comes in many forms, logical possibility, nomological possibility, metaphysical possibility, physical possibility and so on. For the purpose of my argument, I will only consider logical possibility and physical possibility. On the other hand, there are two types of conceivability, logical conceivability, or conceivability, and physical conceivability, or imaginability. Conceivability is based on human reason and imaginability is based on imagination, or intuition if you like. Below are some examples:

Imaginability:	There is an alien civilisation in the centre of the sun
	Pegasus exists
	Every human being has 3 hands

[7] In this context, conceivability imaginability and perceivability are used interchangeably.

Unimaginability:	n-dimensions for n is greater than 3
	Colours other than rainbow colours
Inconceivability:	Square-circle exists
	Truths are false

The limit of the imaginability is constrained only by the imagination of a subject. That is imaginability is subjective, namely whether or not something is imaginable depends on the people who try to imagine it. Say, a colour-blind person may be not able to imagine colour red. Nonetheless, the person cannot infer that colour red is impossible. Whereas the limit of the conceivability is bounded in reason. Take the examples above, square-circle is inconceivable and whatever is inconceivable is unimaginable. Hence, I conclude that:

If A is imaginable, then A is conceivable

Equivalently,

If A is inconceivable, then A is unimaginable

Now, how does conceivability links to possibility. For my purpose, I will take David Hume as my reference. In Hume's *A Treatise of Human Nature*, Hume remarks that:

> '…whatever the mind clearly conceives includes the idea of possible existence, or in other words, nothing we imagine is absolutely impossible' (Hume 1978 p.32)

Hume's idea of absolute possibility is:

A is absolute possibility if and only if A does not derive contradiction

For Hume, there are two kinds of falsehood. The first type of falsehood is that if one attempts to thinks, imagine or conceive *not-A*, it will infer contradiction, because the idea of *not-A* itself is self-inconsistent and self-contradictory, or it is self-evident that *not-A* must be false. Hence, *not-A* is absolutely impossible, like the inconceivability examples above. Another type of falsehood is that to think of *not-A* does not lead self-contradictory, although *not-A* is false. In other words, *not-A* is not self-contradictorily false if and only if one is able to think, imagine or conceive *not-A* as if it were true (Pap, 1958, p. 75)

I think Hume is right that whatever is conceivable is not absolutely impossible:

If A is conceivable, then A is logically possible

Now, I shall argue that the converse is also true, *if A is inconceivable, then A logically impossible*. In my view, logical impossibility and inconceivability have definitional relations, namely they are conceptually connected. The reason why we know something is logically impossible is because we try to conceive it. We fail to conceive it, so we conclude that it is logically impossible. Take the square-circle as an example. By definition, a square and a circle have four corners and no corner. To conceive a square-circle, we need to conceive a square and a circle. However, as soon as we try to conceive a square with no corner or a circle with four corners, our mind start to jam and break down. We realise that we cannot go any further, other than conceiving them individually. This example demonstrates nicely what Hume calls absolute impossibility. The idea of square-circle itself is self-contradictory. Therefore, we have:

If A is inconceivable, then A is logically impossible

5.2.2 Kant on Space

In Kant's *Critique of Pure Reason*, Kant presents an argument on how we, human beings, acquire *concepts*.

> *'Whatever the process and the means maybe by which knowledge refers to its objects,* intuition *is that through which it refers to them immediately, and at which all thought aims as a means. But intuition takes place only insofar as the object is given to us. This again is only possible, for us human beings at least, when the mind is affected by objects in a certain way. The capacity (receptivity) to obtain representations through the way in which we are affected by objects is called* sensibility*. Objects are therefore* given *to us by means of our sensibility. Sensibility alone supplies us with* intuitions*. These intuitions are* thought *through the understanding, and from the understanding there arise* concepts*. But all thought must, directly or indirectly, by way of certain characteristics, refer ultimately to intuition,*

and therefore, with us, to sensibility, because in no other way can any object be given to us' (Kant, 1781, p. 59).

Kant thinks that the objects we see in our daily life, like cups, tables, cars etc. are representations of the objects. They are just representations because we recognise the objects through our sensations, or sensibility, as Kant calls them. These sensations are the reason we see, touch, smell, hear, taste and so on, to connect with the empirical world. Furthermore, apart from all these sensibility, which give us empirical contents, Kant argues, there are some underlying entities, which makes our sensibility possible, that are pure intuitions, which is the pure form of sensibility. These pure intuitions exist *a priori* in our mind and, for Kant, these pure intuitions are *space* and *time* (Kant, 1781, p. 60).

The notions of space and time play a significant role in Kant's philosophy. For Kant, space has four essential features, non-empirical, necessary *a priori*, non-relational and infinite *given* magnitude (Kant, 1781, p. 68). Firstly, space is not empirical, in the sense that space is not derived from experience. Secondly, Kant argues that *the representation of being no space is impossible*. One can think of a space with no object, but it is impossible for one to think of no space at all. Thirdly, space is not relations of objects, but a pure intuition.

In general, Kant places space and time at very special positions in his philosophy. From my understanding, the reason why, for Kant, space and time are not concepts but pure intuition because we need to have space and time first in order to acquire concepts. Here are some examples from his *Prolegomena to Any Future Metaphysics*. Kant argues that pure mathematics and geometry are synthetic *a priori* because when we want to figure out 5+7=12, we need to imagine or conceive something to help us, like 5 fingers adding 7 fingers or 5 dots adding 7 dots will gives 12 dots. Imagining the dots or fingers require pure intuitions, which are space and time. In geometry, when we think of a triangle, we need to have a blank space, then a triangle can be drawn in the space (Kant, 2001, p. 12).

The concept of space and time underlie the intuition of human reasoning. Whenever we try to reason, it is necessarily involved the notion of space and time. In another perspective to look at Kant's concepts of pure intuition, space and time are necessary condition for conceivability. To reason is to conceive. Hence, I would conclude that, without space and time, the act of conceiving is not even possible.

5.2.3 The Impossibility of the State of Spacelessness

Now, if what I have argued above is true, then my argument below will follow:

1. If A is inconceivable, then A is impossible
2. Spacelessness is inconceivable
3. Spacelessness is impossible

I shall argue that spaceless state is inconceivable, namely phenomenologically, we have to perceive space. As the very definition of conceivability itself involves space.

5.3 Final Thoughts

Here, we come to an end. There are some concluding thoughts I draw from this entire thesis.

Firstly, the very critical misunderstanding about substantial space is to think of substantial space like a container. We still are in the search of the nature of space or spacetime. I believe space is not as simple as a container. Space have some bizarre characteristics, like space prevents things to move too fast in reference frames; when it moves near speed *c* in a reference frame, space is contracted and time is dilated in the reference frames; and so on.

Secondly, in the study of physics, substantivalists may not be as convincing as relationalists. However, as soon as metaphysics is concerned, relationalists are in disadvantageous state. They lack an account of what it is to be spaceless. In general, physics and metaphysics is inseparable. One cannot consider physics, as the study of science alone without metaphysics.

Thirdly, I do not agree to categorise Leibniz as a relationalist. Unlike relationalists, Leibniz argues against Newton in term of ontology and metaphysics. Leibniz does not consider the question ‘is the notion of absolute space useful?’, but directly attack on the notion of absolute space.

Finally, with Ismael's remark, (Ismael, 2011, p. 12), every perceptual content, even for the finest perception, must perceive spatial and temporal interval. We are never aware of a point in space but some finite spatial interval. We are never aware of an instance but some finite temporal interval.

References

Armstrong D.M. 1978, Nominalism and Realism: Volume 1: Universals and Scientific Realism, Cambridge University Press, Cambridge.

Baker D.J. 2010, Symmetry and the Metaphysics of Physics. Philos. Compass 5, 1157–1166.

Barbour, J.B., 1982. Relational Concepts of Space and Time. Br. J. Philos. Sci. 33, 251–274.

Berzi, V., Gorini, V., 1969. Reciprocity Principle and the Lorentz Transformations. J. Math. Phys. 10, 1518–1524.

Black, M., 1952. The Identity of Indiscernibles. Mind 61, 153–164.

Colyvan, M., 2015. Indispensability Arguments in the Philosophy of Mathematics, in: Zalta, E.N. (Ed.), The Stanford Encyclopedia of Philosophy.

Colyvan, M., 1998. Can the Eleatic Principle Be Justified? Can. J. Philos. 28, 313–335.

Dasgupta, S., 2015. Substantivalism vs Relationalism About Space in Classical Physics. Philos. Compass 10, 601–624.

Disalle, R., 1994. On Dynamics, Indiscernibility, and Spacetime Ontology. Br. J. Philos. Sci. 45, 265–287.

Earman, J., 1989. World Enough and Space-Time: Absolute Vs. Relational Theories of Space and Time.

Einstein, A., 1961. Relativity. Crown Publisher, New York

Ellis, B., 1990. Truth and Objectivity. Blackwell, Oxford.

Field, H., 1989. Realism, Mathematics & Modality. Basil Blackwell.

Field, H., 1984. Can We Dispense with Space-Time? PSA Proc. Bienn. Meet. Philos. Sci. Assoc. 1984, 33–90.

Hoefer, C., 1998. Absolute versus Relational Spacetime: For Better or Worse, the Debate Goes on. Br. J. Philos. Sci. 49, 451–467.

Huggett, N., Hoefer, C., 2015. Absolute and Relational Theories of Space and Motion, in: Zalta, E.N. (Ed.), The Stanford Encyclopedia of Philosophy.

Ismael, J., 2011. Temporal Experience, in: Callender, C. (Ed.), The Oxford Handbook of Philosophy of Time. OUP Oxford.

Kant, I., 2001. Prolegomena to Any Future Metaphysics: and the Letter to Marcus Herz, February 1772, 2 edition. ed. Hackett Publishing Company, Inc., Indianapolis.

Kant, I., 1781. Critique of Pure Reason. Penguin Classics, London.

Lightner, D.T., 1997. Hume on Conceivability and Inconceivability. Hume Stud. 23, 113–132.

Maudlin, T., 2012. Philosophy of Physics: Space and Time. Princeton University Press, NewJersy.

Maudlin, T., 2011. Quantum Non-Locality and Relativity: Metaphysical Intimations of Modern Physics, 3 ed. Wiley-Blackwell, Malden, MA.

Maudlin, T., 1993. Buckets of Water and Waves of Space: Why Spacetime is Probably a Substance. Philos. Sci. 60, 183–203.

McDonough, J.K., 2014. Leibniz's Philosophy of Physics, in: Zalta, E.N. (Ed.), The Stanford Encyclopedia of Philosophy.

Mermin, N.D., 1984. Relativity without light. Am. J. Phys. 52, 119–124.

Misner, C.W., Thorne, K.S., Wheeler, J.A., 1973. Gravitation. W. H. Freeman, San Francisco.

Nerlich, G., 2010. On The Sovereign Independence of Spacetime. URL http://philsci-archive.pitt.edu/5483/ (accessed 10.6.16).

Nerlich, G., 1982. Special Relativity Is Not Based on Causality. Br. J. Philos. Sci. 33, 361–388.

Newton, I., 1729. The Principia: Mathematical Principles of Natural Philosophy. University of California Press, Los Angeles.

Pap, A., 1958. Semantics and Necessary Truth: An inquiry into the foundations of analytic philosophy. Yale University Press.

Pelissetto, A., Testa, M., 2015. Getting the Lorentz transformations without requiring an invariant speed. Am. J. Phys. 83, 338–340.

Reichenbach, M., Cohen, R.S. (Eds.), 1978. Hans Reichenbach Selected Writings 1909–1953. Springer Netherlands, Dordrecht.

Rickles, D., 2016. The Philosophy of Physics. Polity Press, Cambridge.

Sen, A., 1994. How Galileo could have derived the special theory of relativity. Am. J. Phys. 62, 157–162.

Sklar, L., 1974. Space, Time, and Spacetime. University of California Press, Berkeley, California.